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Greenhouse gas emissions in US beef production can be reduced by up to 30% with the adoption of selected mitigation measures

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Greenhouse gas (GHG) emissions from beef production in the United States are unevenly distributed across the supply chain and production regions, complicating where and how to reduce emissions most effectively. Using spatially explicit life cycle assessment methods, we quantify the baseline GHG emissions and mitigation opportunities of 42 practices spanning the supply chain from crop and livestock production to processing. We find that the potential to reduce GHGs across the beef sector ranges up to 30% (20 million tonnes CO_2e reduced and 58 million tonnes CO_2 sequestered each year relative to the baseline) under ubiquitous adoption assumptions, largely driven by opportunities in the grazing stage. Opportunities to reduce GHGs in the feed, grazing and feedlot stages vary across regions, yet large-scale adoption across the entire beef supply chain is important. These findings reveal promising locations and practices to invest in to advance mitigation goals and an upper-end theoretical potential for mitigation in the beef industry.

The United States is the world's largest beef producer and fourth largest exporter, processing ~33 million head of cattle to produce over 12.3 million tonnes (Mt) of beef each year[1,2]. While providing an important source of food and supporting the livelihoods of millions, it results in 201 Mt of greenhouse gas (GHG) emissions each year, or 3.3% of total US emissions[3,4]. The industry has made meaningful gains in efficiency over the past 50 years[5] in the United States, and beef supply chain actors, including producers, feedlot operators, processors and retailers, are increasingly committed to further reducing GHG emissions[6–9] in response to the growing urgency and direct, material impacts of the climate and biodiversity crises. However, identifying where and which intervention strategies to prioritize remains a substantial challenge and barrier to progress due, in part, to the fact that emissions vary spatially and by production context, influencing where mitigation strategies are likely to be more or less effective (or even detrimental) for reducing production emissions[10–14].

The US beef supply chain is one of the most complex food production systems in the world[15,16], and like many agricultural supply chains, lacks transparency, which prevents processors, food companies and other key downstream decision-makers from identifying where and how to most effectively target efforts to reduce and mitigate GHG emissions[12,13]. Because the movement of cattle and feed through the various stages of production (Fig. 1) is currently not traceable in the United States[17], models are needed to estimate subnational commodity flows and corresponding impacts unique to different regions[18–20]. Existing life cycle assessment (LCA) models aggregate impacts by

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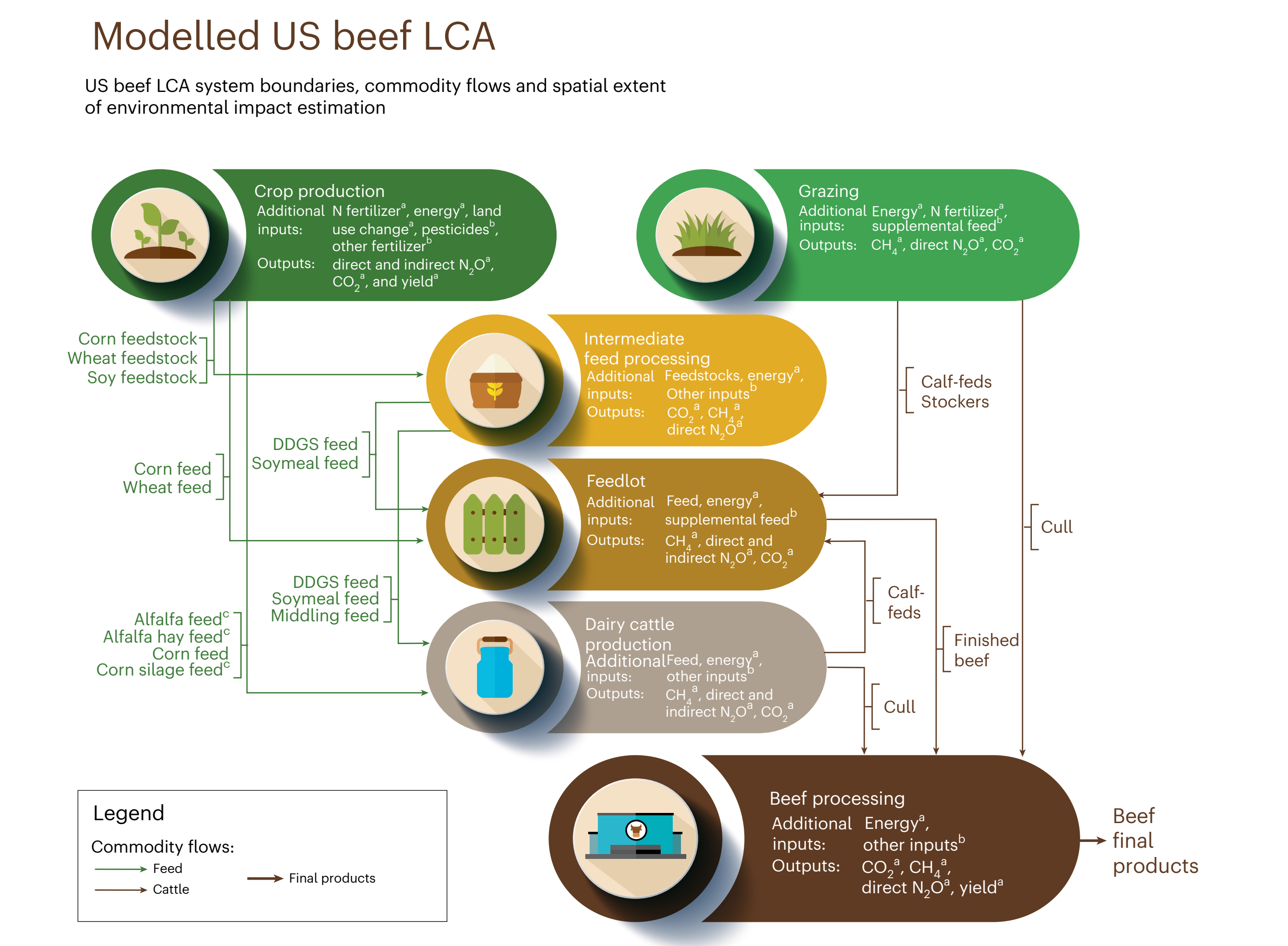

Fig. 1 | Modelled US beef LCA. Stages, flows, system boundaries and spatial resolution of the US beef LCA. LCA parameters: [a]spatially explicit parameters, [b]US averages, [c]yields and land use change are spatially explicit; all the other inputs and outputs are based on US average data.

commodity categories and do not connect these subnational flows to spatially explicit environmental impacts. Consequently, they do not estimate the reduction potential of regionally specific production practices nor the unique relationships that result in spatially variable impacts in downstream stages of the supply chain[3,11,21–23]. Characterizing such differences across production stages and regions is critical to prioritizing and deploying interventions.

Here we present a spatially explicit, fine-scale 'cradle-to-gate' assessment of GHG impacts and mitigation opportunities (Table 1) of the US beef supply chain. We identify emission hotspots and quantify individual and combined reduction potentials from applying different interventions across locations and stages of the supply chain. This is accomplished by linking the spatially determined impacts of production across the entire beef supply chain with a transport cost-minimization model that connects subnational agricultural commodity flows (feed and cattle) and individual beef processing facility demand (Fig. 1 and Supplementary Figs. 1–4). This approach bridges a critical gap in information necessary for decision-makers to prioritize the deployment of emission mitigation strategies in the US production system, propelling the industry to meet climate action targets. While we present a prospective, theoretical potential for different strategies to mitigate emissions considering existing practices and key biophysical constraints, other feasibility constraints related to economic, social or other factors are important to examine in future research. As such, our results are presented as a high-end estimate of what could be reached under ubiquitous adoption assumptions, assuming typical economic, social or other feasibility constraints can be overcome through market and regulatory incentives and technical improvements. It is also important to note that the selected list of strategies examined here spans those that may reduce emission sources directly and those that may increase the carbon sequestration potential of working lands (Tables 2 and 3); it does not represent an exhaustive list of opportunities, but rather those that have been touted in the industry as possible routes to meet climate action targets and those that can be examined within this study's current analytical approach. Other strategies, such as changes in feed diets and productivity improvements, are outside the scope of our study but are also important opportunities to be examined in future research (see section 2.4 of Supplementary Information for additional discussion).

Aggregate US beef industry baseline emissions

We find that the US beef industry currently emits 257.5 Mt $CO_2e\ yr^{-1}$ in total (Fig. 2), with 15% attributed to feed production, 64% to grazing, 19% to confinement and 3% to processing. Across all processing facilities, fed-beef generates an average of 32.6 $kgCO_2e\ kg^{-1}$ boneless beef, culled beef generates approximately 30.0 $kgCO_2e\ kg^{-1}$ boneless beef and culled dairy cows generate 14.5 $kgCO_2e\ kg^{-1}$ boneless beef owing to much of the impacts allocated to dairy products. These estimates are comparable to others published that are based on national average inventories[3,22]. Unlike previously published methods for estimating the US beef industry emissions, this model also enables the assessment of subregional patterns and identification of hotspots of mitigation

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Table 1 | Mitigation practices explored by US beef supply chain stage

Supply chain stage	Mitigation practice	Description of practice	Mitigation pathways	Description of pathways
Crop production	Cover crops[a]	Crops grown after a cash crop harvest, which have the potential to increase soil organic matter; improve water infiltration, soil structure and fertility; reduce erosion; and provide pest management functions; practice modelled includes both seasonal leguminous and non-leguminous cover crops	RE, CS	Increased soil carbon storage, reduced fertilizer use resulting in reduced upstream emissions from fertilizer production, and direct and indirect N_2O emissions
	Conservation tillage[a]	A shift in tillage practice that reduces soil disturbance and leaves more residue on the field, including reduced till, in which >30% of residue is left on the field; strip till, in which crops are planted in a narrow cultivated band no more than a third of the row width, leaving 70% of the soil undisturbed; and no till, in which tillage is essentially eliminated and more than 70% of residue is left on the field. Modelled changes to tillage practices include changing from intensive till to no till and strip till, or reduced till, and changing reduced till to no till and strip till	RE, CS	Increased soil carbon storage, reduced fuel use on the farm and reduced direct nitrous oxide emissions in the field
	Nutrient management[a]	Practices that match nutrient availability to crop demand to minimize the loss of nitrogen through leaching, denitrification and volatilization, including the '4Rs': right type of fertilizer, right placement, right timing and right amount	RE	Reduction of upstream emissions in fertilizer production, reduction of direct and indirect nitrous oxide emissions
	Irrigation[a]	Practice of artificially supplying water to address crop water requirements and improve crop growth; practices modelled that reduce emissions: variable rate irrigation, improving irrigation efficiency (equipment, timing, precision) and switching to renewable energy	RE	Reduction of energy use associated with pumping and distribution of water, reduced emissions from alternate energy use for irrigation
	Telemetrics	Practice of optimizing fleet operation management on the farm through the use of technology that provides real-time data around soil and crop nutrient and water requirements	RE	Avoided emissions through improved energy, fuel and nutrient use
	Land use change moratorium	Avoiding future land use changes from cropland expansion via, for example, conservation easements	RE	Avoided carbon loss and nitrous oxide emissions from N mineralization
Grazing	Prescribed grazing[a]	Approach to improve pasture condition by managing the harvest of vegetation with grazing animals	CS	Increased plant biomass and carbon in roots and soil
	Riparian forest restoration[a]	Practice that restores degraded riparian areas by planting woody plants	CS	Carbon storage in new plant biomass
	Riparian restoration	Practice that restores degraded and drained wetland systems by reestablishing and restoring riparian ecosystems; focal area for application: Northern Great Plains Prairie Pothole Region	CS	Increased soil carbon storage in riparian vegetation
	Rangeland planting[a]	Practice that involves seeding underperforming grazing lands to increase species diversity and forage production	CS	Increased plant biomass and allocation of carbon to roots and soil
	Silvopasture*	A type of agroforestry in which trees are added to grazed lands	CS	Carbon accrual in tree biomass
	Adaptive multi-paddock grazing	Practice in which pasturelands are managed using high stocking densities and rotated quickly to increase plant production and soil carbon storage, especially effective in places with degraded soils and enough rainfall to support high plant production	CS	Increased productivity and soil carbon storage
Feedlot	Feed additive (3NOP)	Application of a feed additive to inhibit enteric methane production at the feedlot; based on the availability of independent, peer-reviewed studies, the feed additive containing 3NOP was selected to represent the potential impact of feed additives in this model; products containing 3NOP are not currently USDA approved but are anticipated for approval in alignment with current EU policies and the proposed US 'Innovative Feed Enhancement and Economic Development Act of 2023' (Innovative FEED Act)	RE	Reduction of ruminant methane production
Dairy operations	Feed additive (3NOP)	Application of a feed additive (3NOP) to inhibit methane production in the rumen in dairy management	RE	Reduction of ruminant methane production
	Solids separation	Solid separation, a form of manure management that reduces methane and nitrous oxide production by reducing anoxic conditions; practices modelled: uncovered lagoons with gravity separation and mechanical separation, deep pits with gravity separation and mechanical separation	RE	Reduction of methane and nitrous oxide emissions from manure in storage
	Anaerobic digestion	AD, a manure management technology that can help reduce methane and nitrous oxide losses during storage and offset fossil fuel use by producing electricity; practices modelled: shifting from an uncovered manure lagoon to covered lagoon with an AD, shifting from an uncovered lagoon to a complete mix or plug flow AD	RE	Reduction of methane and nitrous oxide emissions from manure in storage, offset upstream fuel use for electricity production through co-production of energy
Processing	Energy management	Efforts to improve efficiency or change energy sources in beef processing plants; practices modelled: electric energy efficiency, thermal energy efficiency and 100% wind electricity	RE	Reduced upstream emissions through a different source or reduced use of electricity and energy

Mitigation practices included in this analysis and corresponding mitigation pathways are described for each supply chain stage: crop production, grazing management, feedlot management, dairy management and processing (see Supplementary Table 33, pages 51–54, for assumptions of individual and combined practice scenarios and section 3 of Supplementary Information for references). We highlight the mitigation pathways—reduced emissions (RE) and carbon storage (CS)—and include notes to further describe them. Mitigation potential and pathways are context dependent and encompass a degree of variability and uncertainty. 3NOP, 3-nitrooxypropanol; AD, anaerobic digestion. See the descriptions of the methods of sections 3.1–3.4 in Supplementary Information for additional details on assumptions and Supplementary Table 34 for each mitigation practice. [a]USDA Natural Resource Conservation Service Conservation Practice Standards or included in these standards[40].

Table 2 | Key assumptions for mitigation opportunity modelling

Supply chain stage	Mitigation practice	Locations applied
Crop production	Cover crops	All corn and soybean cropland currently not adopting cover crops; croplands currently irrigated assume application of irrigated cover crops, whereas unirrigated croplands assume application of unirrigated cover crops
	Conservation tillage	Based on the baseline distribution of tillage systems deployed for corn and soybean cropland; all current intensively tilled croplands switch to either no-till or reduced-till practices, and all current reduced-till croplands switch to no till
	Nutrient management	Based on timing of N application and soil conditions relating to vulnerability of leaching and runoff; applied to corn crop production
	Variable rate irrigation	All remaining corn croplands that deploy powered irrigation systems that have not already adopted technology
	Irrigation energy efficiency & renewables	Based on baseline distribution of different energy-powered irrigation systems
	Telemetrics	All corn and soybean crop production based on remaining adoption potentials
	Land use change moratorium	All corn and soybean croplands with existing rates of land use changes
Grazing	Prescribed grazing	All grazing areas assumed to be degraded (ranking fair, poor and very poor), amounting to an average of 61% of grassland and grazing acres
	Riparian forest	30 m riparian buffers on either side of a stream or water body in pastureland acres deemed suitable for reforestation
	Riparian restoration	Grazing areas assumed to be degraded (ranking fair, poor and very poor) in 30 m riparian buffers on either side of a stream or water body in the Prairie Pothole Region of the Northern Great Plains
	Rangeland planting	All grazing areas assumed to be degraded (ranking fair, poor and very poor), amounting to an average of 61% of grassland and grazing acres
	Silvopasture	Pastureland acres deemed suitable for reforestation, excluding 30 m riparian buffers in states that have been historically forested and in which county-scale carbon storage rates are available
	Adaptive multi-paddock grazing	Managed pastures in mesic areas assumed to be degraded (ranking fair, poor and very poor) in the Midwest and southeast
Feedlot	3NOP feed additive	All fed-beef for the duration of confinement as an emerging technology solution assuming commercial approval in the United StatesDairy
Dairy operations	3NOP feed additive	All dairy cows not in pasture, range and paddock systems as an emerging technology solution assuming commercial approval in the United States
	Manure management: solids	All manure currently handled in uncovered lagoon and deep pit storage systems; estimated for gravity and mechanical separation processes
	Manure management: anaerobic digestion	All manure currently handled in uncovered lagoons and liquid and slurry systems based on current state-level distribution of management systems
Processing	Energy management	All processing locations

Here we outline some of the pertinent details on where mitigation practices were applied for this analysis, with descriptions of practices included in Table 1 and additional details on assumptions and emission reduction and carbon storage potentials included in Supplementary Tables 33 and 34 and Supplementary Sections 3.1–3.4.

opportunities for different actors along the supply chain. Generally, findings indicate absolute emissions from feed production associated with beef sourcing, and confinement (primarily feedlots) is concentrated in the Great Plains and Midwest regions, whereas emissions from grazing tend to be more evenly distributed across the western United States (Fig. 3). Emissions associated with the processing stage are localized around processing facilities; the highest densities of these facilities occur in close proximity to confinement operations (that is, in the Great Plains), but there are also emission hotspots associated with processing occurring in the northeastern and southwestern regions (Fig. 3).

Spatial distribution of beef emissions and emission intensity

Our model shows that emissions from feed, grazing, confinement and processing vary across the country, including at the county scale (Fig. 3). The grazing stage generates the majority of emissions (64%) owing firstly to the duration of this phase in cattle life cycles (for example, beef cows spend upwards of 2,400 days on pastureland, with calves and stockers spending around 450 days grazing, compared with about 145 days spent in feedlots) and secondly to the differences in feed efficiency between the average diet of cattle in the grazing stage compared with confined feeding operations. That is, cattle fed concentrates (for example, corn, dried distiller grain with solubles (DDGS) and wheat-based feed products) in feedlots emit fewer GHGs per unit of feed compared with cattle consuming grass and other forage because of the higher digestible energy content of concentrates. These findings are similar to those of other studies comparing GHG impacts of grain-finished and grass-finished cattle systems[24] for US beef production[3,22], which also indicate that a majority of baseline emissions can be attributed to enteric fermentation and manure generated while cattle are grazing. Total emissions for a given county are thus a result of the number of cattle produced in each county and the associated emission intensity, with counties specializing in grazing operations often having higher emissions than those specializing in confinement operations, with the exception of a few large confinement operations in the central United States and parts of California that support substantial cattle populations. Production of feed concentrates and consumption of feed in confinement generates 34% of total emissions. Our model estimates that a large proportion of emissions generated from feed production occurs in Great Plains states such as Nebraska and Kansas, which represent key sourcing regions for feedlots.

Emission intensity, defined here as kg of CO_2e emissions per kg of boneless beef at the processing gate, is also distributed and varies across counties, driven in part by downstream assumptions of

Table 3 | Total US beef industry GHG and estimated mitigation potential (Mt CO_2e) across production practice scenario combinations

Category	Category detail	Baseline (Mt CO_2e)	Future emission potential with mitigation scenarios (Mt CO_2e)	Short-term carbon sequestration scenarios (Mt CO_2e)	Future emission potential with mitigation and carbon sequestration scenarios (Mt CO_2e)
Feed	Corn and DDGS	32.824	23.530	−10.143	13.387
	Soymeal	1.767	0.907	−0.325	0.582
	Other feed	3.651	3.651		3.651
Transport	Feed	0.572	0.572		0.572
	Animal	0.323	0.323		0.323
Grazing	Enteric fermentation	111.608	111.608		111.608
	Manure	40.468	40.468		40.468
	Pasture	3.338	3.338	−47.730	−44.392
	Other	8.022	8.022		8.022
Feedlot	Enteric fermentation	21.031	16.368		16.368
	Manure	16.591	16.591		16.591
	Other	2.026	2.026		2.026
Dairy	Enteric fermentation	6.491	2.966		2.966
	Manure	1.768	1.768		1.768
	Other	0.126	0.126		0.126
Processing	Primary	5.207	3.387		3.387
	Secondary	1.699	1.699		1.699
Total		257.512	237.350	−58.198	179.152

Estimates correspond to Fig. 2 totals.

processing yields associated with particular cattle types and sourcing regions (for example, culled cows versus stockers), as well as differences in primary productivity (for example, crop yields, net primary productivity of forage). The influence of these variables can cause noticeable differences in the location of hotspots for emission intensity of a particular stage compared with the same stage's total emission. For example, in some feed production regions outside the Midwest, such as in the northeastern United States, high-emission-intensity hotspots (Fig. 3b) due to lower-than-average yields in these regions (as well as other differences in production[20]) are conversely associated with relatively low total emissions (Fig. 3a) because of the smaller quantities of feed sourced from these areas. Identifying regions that have both high emission intensity and high total emissions, such as the Nebraska and Kansas feed production regions, helps highlight the key areas for prioritizing investments to efficiently reduce emissions within the sector. Emissions from grazing are primarily caused by enteric fermentation in beef cows, which are mostly reared on the rangelands of the western United States and attributed in part to offspring that are then supplied to confinement operations. These rangelands are characterized by lower-quality forage, as measured by total digestible energy. This results in reduced digestive efficiency in cows, leading to increased methane emissions due to the higher fibre content of their diet. Emission intensities in the northeast United States and southern California are lower than those of other production areas owing to the influence of culled dairy cows and calf-fed dairy cattle in the supply chain. In addition to inherent efficiencies within the calf-fed dairy cattle production system, such as the steer's overall shorter lifespan (Supplementary Table 8) in regions practicing lightweighting and reduced time spent grazing, the attribution of the majority of the emissions from dairy cow production to milk products[25] reduces the emission intensity of beef sourced from culled dairy cattle compared with other systems (Supplementary Figs. 3 and 4).

Potential for GHG mitigation in the beef supply chain

Across the US beef industry, we find that 30% of the baseline GHG emissions could be mitigated through full implementation of alternative practices (summarized in Tables 1 and 3) in the feed production (8%), grazing (19%), confinement (3%) and processing (1%) stages, equivalent to 20 Mt CO_2e reduced and 58 Mt CO_2 sequestered each year relative to the baseline (Fig. 2). The majority of the emission mitigation potential exists in the grazing stage, which is also the most emission-intensive part of the supply chain (Fig. 2). These grazing management strategies are, however, based on relatively short-term carbon sequestration assumptions, with carbon storage potential neutralized after 10 years (given the underlying assumptions of this study). While total magnitudes of soil carbon gains are uncertain, if the sequestration rates used in this study can be realized (see section 3.1 of Supplementary Information and Supplementary Table 34 for specific assumptions), these carbon storage strategies can lead to substantial mitigation potential in the beef supply chain (47.7 Mt CO_2), making them an important pathway for addressing the urgency of climate change alongside strategies that reduce actual emission sources (for example, enteric fermentation) that are also necessary to address climate action needs. We estimate that strategies that reduce emissions in the beef supply chain can mitigate 8% of the emission intensity of beef production. Other strategies that were outside the scope of this analysis, such as opportunities in selective breeding, precision feeding, diet reformulation and other technologies targeting direct reduction of enteric methane production not considered (for example, feed additives with various modes of action, vaccines and so on), may have additional potential reduction benefits[26]. Within each stage of the beef supply chain, we find that stacking mitigation opportunities in feed production could reduce feed emissions by 54% (20.6 Mt CO_2e), which may have co-benefits for reducing emissions for other feed sourcing industries. Implementing a feed additive in

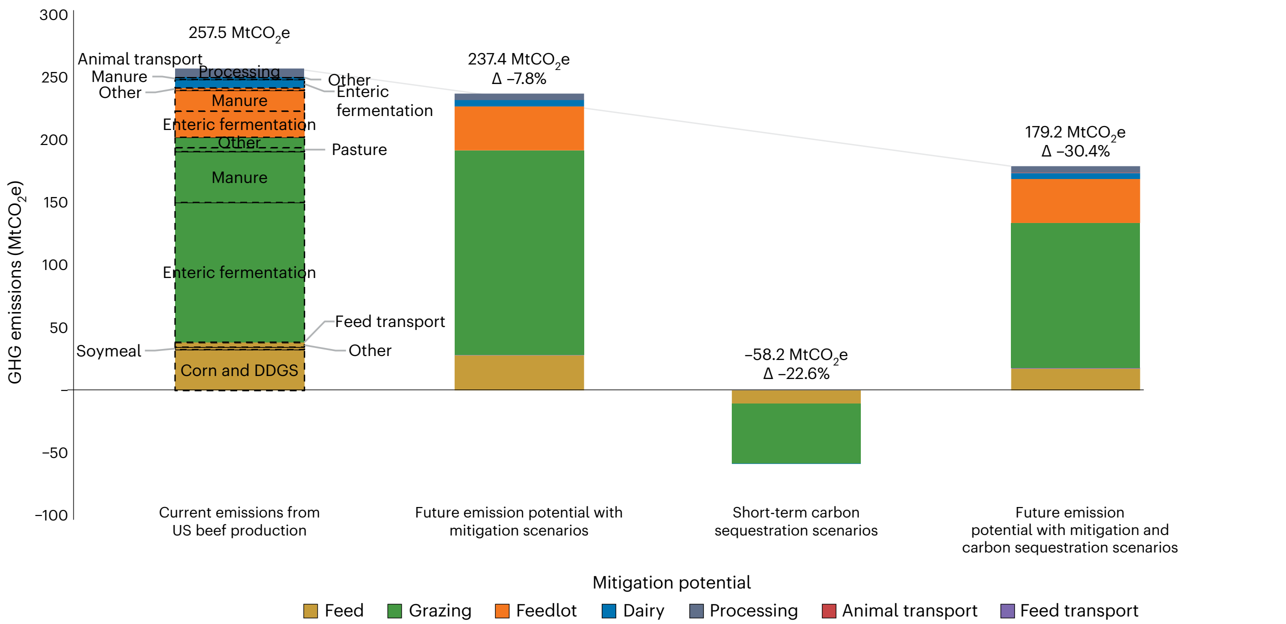

Fig. 2 | Total US beef industry GHG emissions and estimated mitigation potential across sustainable production practice scenario combinations. Practices are grouped and colour coded by production stage (that is, feed, grazing, feedlot, dairy and processing) and correspond to the selected scenario combinations highlighted in Fig. 4. Individual practices and the associated reduction potentials are indicated in Supplementary Table 33 (see Tables 1 and 2 for mitigation scenario details). 'Feedlot' and 'Dairy' are combined as 'Confinement' in Figs. 3 and 4. Negative values represent carbon sequestration potential.

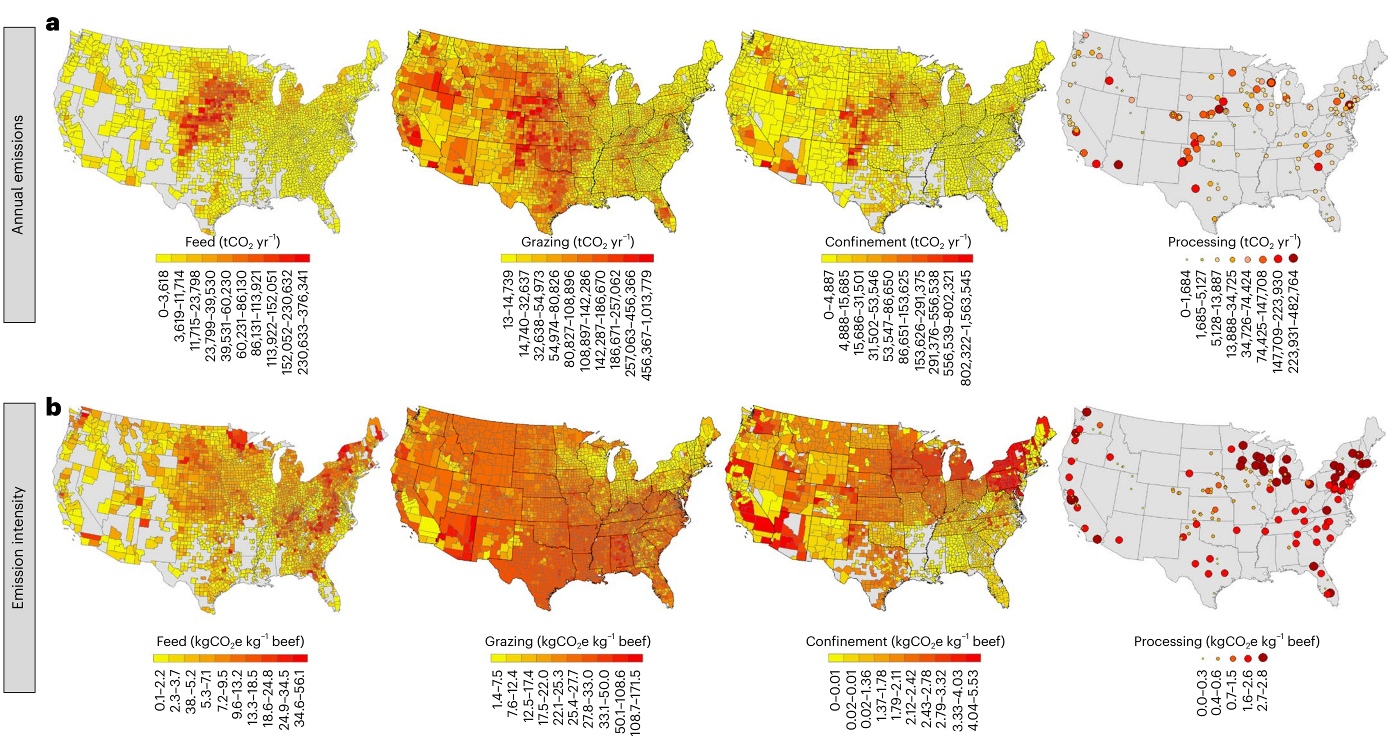

Fig. 3 | Geographic hotspots of US beef industry baseline GHG emissions by production stage. a, Baseline total annual emissions (2017). **b**, Baseline emission intensity ($kgCO_2e\ kg^{-1}$ boneless beef). Production stages include: feed concentrate production, pasture and rangeland grazing, confinement (feedlot and dairy) and processing.

the feedlot could reduce feedlot emissions by 12% (4.7 Mt CO_2e), as enteric fermentation represents about half of the stage's emissions (Fig. 4). Furthermore, a combination of interventions in dairy production, such as manure management, potentially reduces in-stage emissions by 42% (3.5 Mt CO_2e) and the emissions associated with the processing stage could be reduced by 26% (1.8 Mt CO_2e) through energy management strategies (Fig. 4). Notably, the use of silvopasture applied across all eligible land in the grazing stage reduces total cradle-to-gate emissions (from feed production through beef processing) by 13% through carbon sequestration in additional tree biomass (20% within the grazing stage alone), representing the largest single opportunity for mitigating emissions in the beef supply chain in the short to medium

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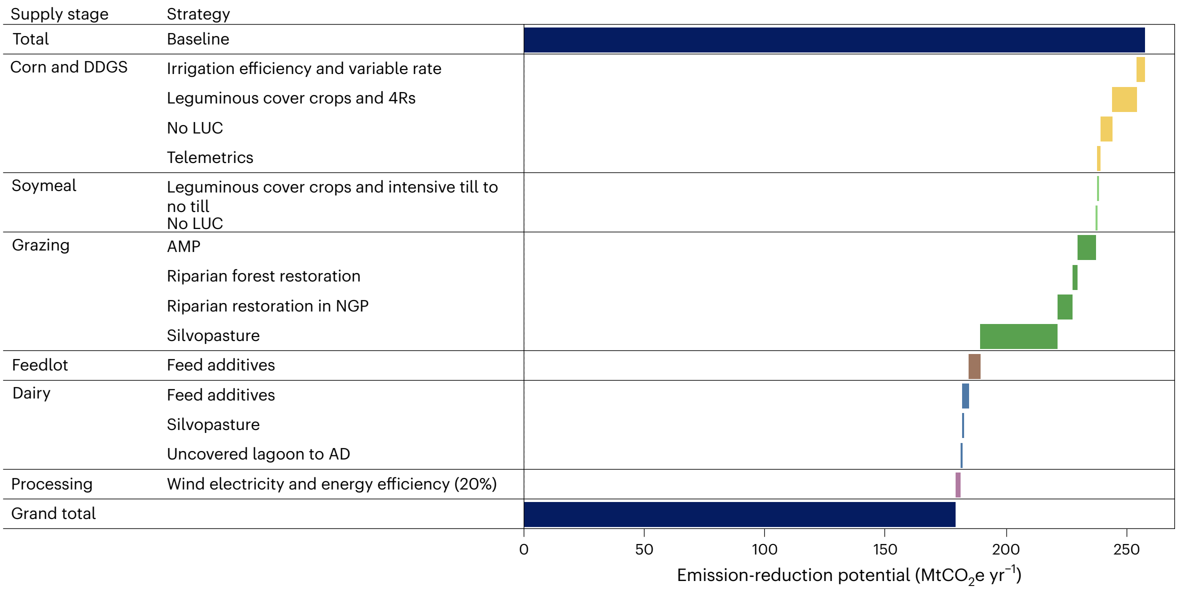

Fig. 4 | US beef industry emission-reduction potential by strategy and supply chain stage. Scenario combinations are shown in Mt CO_2e and are selected based on maximizing the reduction potential for the industry. 4Rs, a nutrient management strategy encompassing right placement, right timing, right type and right amount of fertilizers; AD, anaerobic digestion; AMP, adaptive multi-paddock grazing; LUC, land use change; NGP, Northern Great Plains.

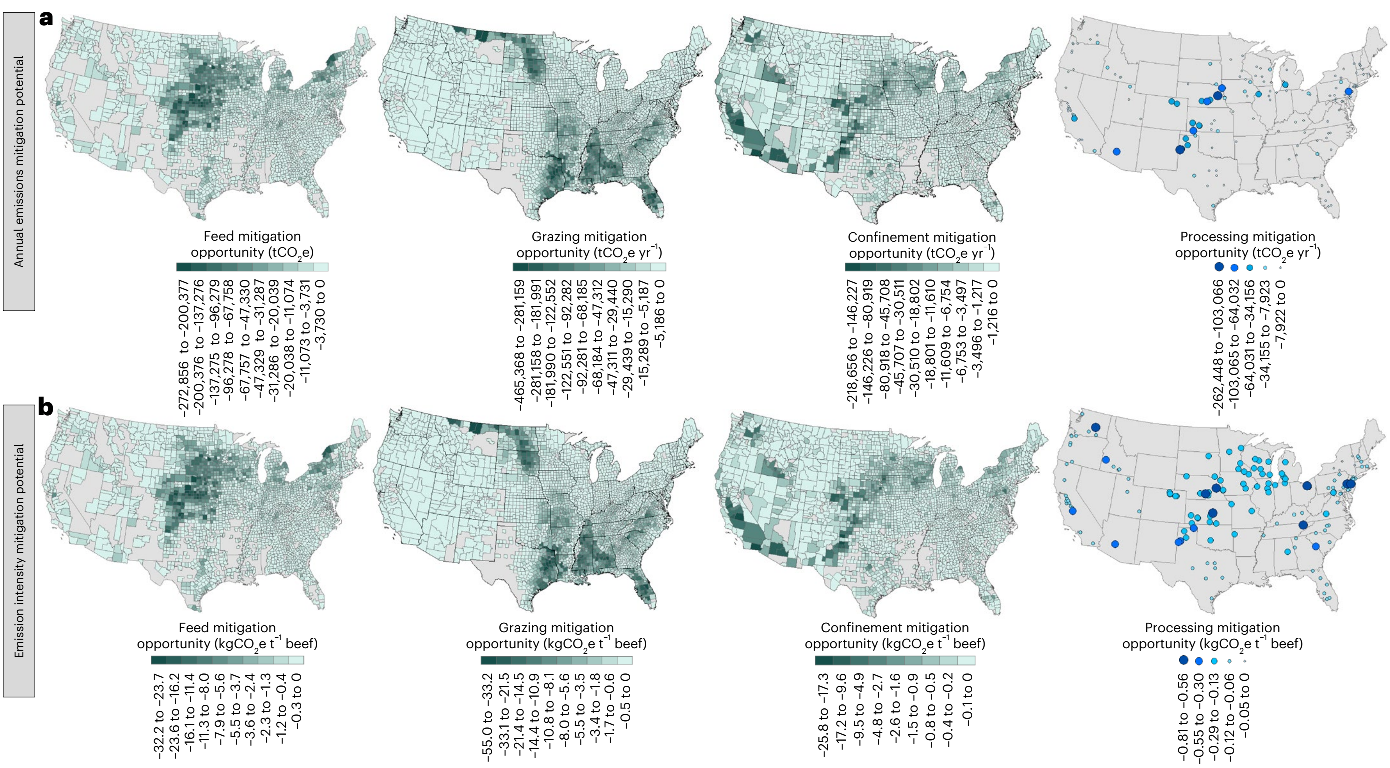

Fig. 5 | Geographic hotspots of US beef industry GHG emission mitigation potential by production stage. a, Total emission-reduction potential per year ($tCO_2e\ yr^{-1}$). **b**, Potential emission-reduction intensity of mitigation opportunities ($kgCO_2e\ t^{-1}$ beef). The production stages include feed concentrate production, pasture and rangeland grazing, confinement (feedlot and dairy) and processing.

term (see Methods, section 3.1.7 of Supplementary Information, and Supplementary Tables 33 and 34 for details on estimation). By contrast, applying nutrient management strategies and cover crops to all applicable feed production lands (that is, the practices with the greatest mitigation potential in the stage; Fig. 4) results in just 4% emission reduction from the overall total baseline (and 27% reduction within the feed stage alone).

Unequal spatial distribution of mitigation opportunities

Mitigation opportunities are also unequally distributed across the United States. We find that the Northern Great Plains and southeastern regions of the United States are hotspots for potential emission reductions (Figs. 5 and 6) because of the carbon sequestration capacity of specific practices within these areas. In the southeastern United

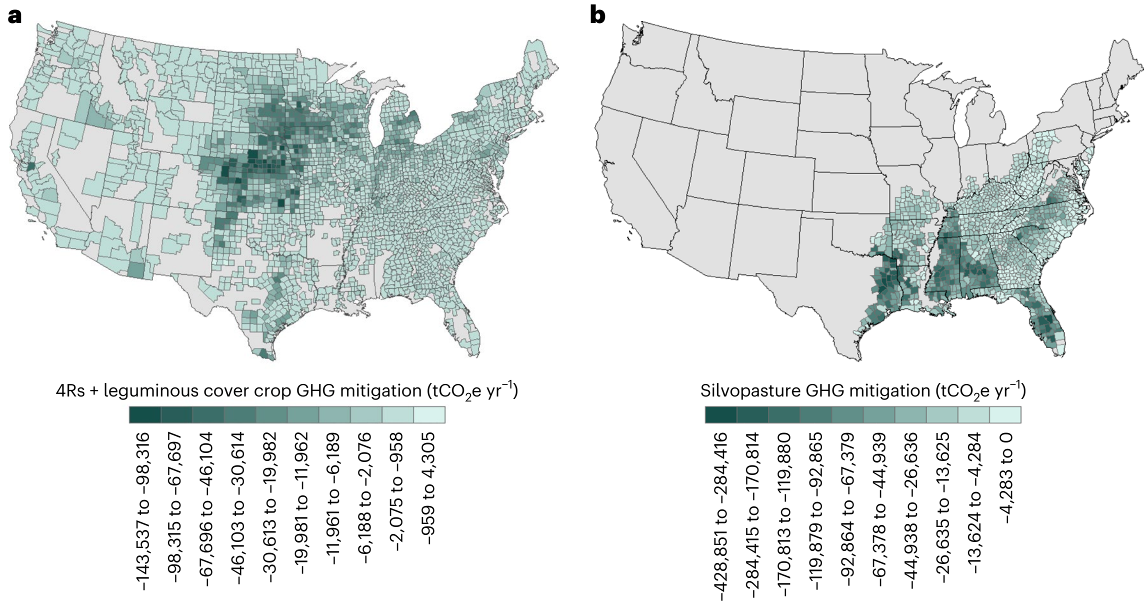

Fig. 6 | Distribution of mitigation potential of practices with the highest estimated potential in the feed and grazing stages. a, 4Rs plus leguminous cover crops in corn production. **b**, Silvopasture on grazing lands.

States, the addition of trees to pasturelands (that is, silvopasture) is an important opportunity for storing more carbon in grazing systems, while in the Northern Great Plains, repairing degraded wetland areas can be a critical intervention. Hotspots for mitigating emissions in feed production coincide with the primary regions where concentrate feed is sourced, namely, the central part of the United States. Increasing the adoption of cover crops and nutrient management practices that reduce fertilizer needs, as well as increasing farm energy use efficiency, especially in pumping for irrigation, can reduce both direct and indirect emissions from feed production. Reducing annual land use change for feed production, that is, the conversion of lands to cropland for the production of feed ingredients, was also highlighted through our analysis and may be particularly relevant in regions experiencing declines in crop or pasture productivity due to soil degradation. Spatial distribution of mitigation opportunities within the confinement stage is limited by the location of feedlots and exhibits less variation between regions than other stages of the beef supply chain. This pattern is driven by two primary factors: (1) manure management systems in beef feedlots are highly similar across locations and (2) we assume a uniform scalar for the reduction potential of feed additives on enteric fermentation (see Supplementary Information section 3.3.1).

The results presented here show that the potential for mitigating emissions is meaningful but varies substantially across crop production and grazing regions owing to the differences in existing production practices, climate and soil conditions. The added detail made possible by this spatially explicit LCA modelling approach shows its importance for identifying key leverage points across regions and supply chain stages. While local ecological, operation and site conditions are critical to inform what practices are most appropriate for a given context, this information provides supply chain actors a critical starting place to be able to identify where and how to deploy resources for mitigation more effectively to advance climate action and more rapidly achieve targets and commitments. Our analysis provides an upper-end estimate of reduction potential assuming broadscale adoption of mitigation practices while incorporating some key conservation-related considerations, for example, limiting silvopasture to areas with historic forests and excluding this practice in native grasslands. There are certainly limits in the feasibility of adoption owing to economic and/or socio-cultural constraints across the country[27,28]; however, showing this full potential highlights what could be possible if those constraints were reduced. Furthermore, there are potential additional benefits[29] or tradeoffs with other environmental, social and economic outcomes[13] that would be critical to consider in any given context in addition to climate change mitigation benefits. As such, decision-makers should leverage evidence- and context-based approaches to facilitate adoption[30] of opportunities across all sectors, especially as some opportunities in some sectors are likely to be more easily implemented than others[29], and may also have co-benefits for reducing emissions in other sectors (for example, reducing the emission intensity of feed concentrates fed to other livestock sectors), which remains an area for future research.

While this study examines the spatial mitigation potential of 42 strategies (Supplementary Tables 33 and 34) available to the US beef sector, many more potential opportunities to reduce emissions exist that warrant further examination. Current and emerging technologies to mitigate enteric fermentation emissions have low or no adoption, but trials and other studies indicate substantial potential[31] and new pathways for the regulation of these technologies are currently being explored. By contrast, there are additional restoration and land-based practices that could have soil carbon storage potential in certain grazing land locations that do not yet have a broad evidence base and need further investigation before they can be properly incorporated into spatially explicit mitigation planning, for example, additional riparian restoration approaches[32,33]. There is also potential to modify feed rations, which will have dynamic, complex effects on feed supply chains, enteric fermentation and manure emissions, and livestock growth and performance. Such complexity requires simulation models such as those deployed in this study, to identify the net outcomes and potential for reducing emissions across the industry to avoid potential leakage and rebound effects. Importantly, we find that under current supply chain conditions, the beef industry has the theoretical potential to mitigate emissions by 30% (8% from emission reductions and 22% from carbon sequestration and storage) through implementation of practices that primarily increase the carbon storage of working lands. Our study identifies which lands within the beef supply chain have the greatest potential opportunity to increase the carbon storage potential through adoption of alternative management practices, providing state and county officials, beef and crop processors, and producers with a road map to mitigate emissions in the industry. This methodological approach serves as an example for other agricultural industries and countries of production to follow for identifying effective and efficient pathways for climate action, as well as for other impact categories of interest like water scarcity and land use. While this study considers the warming potential of emissions over 100 years (that is, GWP100) based on the IPCC Fifth Assessment Report (AR5), which was the latest report available at the time of this study's analysis, new metrics and assumptions such as those presented in the IPCC Sixth Assessment Report (AR6) are available that can be further considered in future analyses[34,35]. For example, GWP100 impacts from methane and nitrous oxides are reduced in AR6 compared with those of AR5, although considering shorter time frames such as the GWP20 or linking more directly to the changes in global temperatures such as through the global temperature potential or GWP* metric would further highlight the substantial impacts of short-lived emission sources such as methane on global temperature increase[34,36]. Including these and other metrics may probably have implications on the relative reduction potential of different strategies and remains an area for future research. While uncertainty and data limitations exist throughout this analysis (see section 2.4 of Supplementary Information), which can be refined as better data become available, the ability to provide geospatial indicators of relative environmental impacts and mitigation opportunities across the beef supply chain is a crucial step towards managing and achieving climate commitments.

Methods

Spatialization of the US beef supply chain

In the United States, commercial beef is produced from a variety of sources, the most common (80%; Supplementary Table 1 (ref. 2)) being from feedlot sources where beef cattle are fattened on high-grain diets. Before cattle enter feedlots, they often graze on roughages from pasture and rangeland. These beef cattle grazing systems maintain cow and calf populations, replacement heifers and stocker cattle. Of the total cattle supplied to feedlots, approximately 41% are supplied by stocker cattle, which typically spend 75% of their lifetime in grazing systems before entering feedlots; 27% are supplied by calves from cow–calf systems at around 310 days of age for a wean weight of 515 lb (these calves are known as calf-feds) and 32% of fed-cattle are supplied by male dairy steers that enter feedlots between an estimated 45 and 263 days of age depending on the region, which correspond to a weaning weight of 150 and 450 lb, respectively. In addition to fed-beef, dairy and beef cows are culled for beef at the end of their economically productive life, making up 9% and 10% of US cattle processed[2,16]. See Supplementary Tables 8 and 9 for further details. Because of the complexity of the multiple stages of production, diversity of sources of inputs and extensive movement of feed and cattle throughout the beef life cycle, GHG accounting methods that incorporate this detailed context are critical.

To model the beef supply chain, we built on the approach of the Food System Supply-Chain Sustainability Model (FoodS^3)[20,37,38] that combines a supply chain optimization model of subnational commodity flows with county-level spatially explicit environmental impacts. The supply chain model uses linear programming to minimize the total impedance of the system, considering county- and facility-scale feed and animal supplies and demand across all sectors of demand. Previous FoodS^3 models[20,37,38] focused on estimating the subnational transfers of corn, DDGS, soybean, wheat and middling feed commodity supplies to various sectors of demand and considered only the 'cradle-to-crop gate' environmental impacts. In this study, we focused on capturing the complexity of the beef supply chain, with pasture and rangelands and dairy operations supplying fed-calf and stockers to feedlots, and feedlots, grazing and dairy operations supplying fed-beef and culled cows to processing facilities. We used the USDA 2017 census to estimate livestock supplies and demand at the county level, and scaled the inventory populations to total commercially slaughtered beef quantities[2]. See section 1 of Supplementary Information for a detailed calculation methodology.

Spatially explicit baseline beef LCA

To assess GHG mitigation pathways, we first constructed baseline life cycle inventories reflecting the material and energy inputs and emissions and intermediate product outputs for each stage of the beef supply chain. We did so by building on initial county-scale average (2007–2017) GHG estimates of feed concentrate ingredients, including corn feed, DDGS, soybean meal, wheat and wheat middlings[20], and further updated these estimates to account for the current annual carbon sequestration of existing cropland conservation practices, including cover cropping, changing tillage regions to reduced or no till, and use of precision agriculture technologies. See section 2.1.1 of Supplementary Information for details on estimation. We further estimated the other feed-related emissions from feed milling and intensively managed pasture systems that use synthetic fertilizers, and include initial spatial GHG estimates of alfalfa, corn silage and alfalfa hay production, which are roughages used in relatively high proportions in dairy production systems (see section 2.1.2 of Supplementary Information and N. Springer et al. (manuscript in progress) for details on estimation). We connected the estimated emissions per unit of feed produced in each area with the downstream demand across feedlot and dairy production locations using the supply chain optimization model, resulting in unique county-scale feed footprints.

We further estimated the GHG emissions associated with on-farm livestock production, including enteric fermentation considering regionally defined diets and forages from the US EPA, manure management considering each type of operation and phase of growth (for example, cow–calf versus feedlot and dairy cow versus dairy heifers), and energy and other materials used on farms considering differences across regions and type of operations. See section 2.2 of Supplementary Information for further details on estimation. The emissions estimated for the grazing stage in the cattle production system were then aggregated based on the county-to-county sourcing information estimated from the supply chain models that detail, for a given feedlot location, the portion of cattle sourced from each category of supply (stockers, calf-feds, dairy steer calves), which was then used as the weights for estimating total grazing stage emissions from fed-cattle.

Finally, we estimated the emissions associated with the processing stage of the supply chain considering the fuel and electricity used, the respective Emission and Generation Resource Integrated Database (eGRID) operating region and the embedded emissions from upstream cattle production. As in the case of the fed-cattle supply, we similarly aggregated emissions for processors, in which direct and embedded emissions from livestock production are combined with supply chain estimates detailing the portion of fed-cattle versus culled beef and dairy cows supplied to each processing facility to meet annual demand.

GHG mitigation opportunities

We examined several GHG mitigation opportunities across each of the different stages of the beef supply chain. Where data were available, we considered the existing penetration of conservation management strategies, such as cover cropping and nutrient management, and examined the potential change in emissions if the remaining runway for adoption were implemented. We used county-level emission-reduction potential across stages and management options, largely relying on COMET-PLANNER[39], which uses biogeochemical models such as DAYCENT to estimate sequestration potentials, for feed management opportunities and some grazing management opportunities. For some mitigation opportunities, we found COMET-PLANNER estimates of GHG mitigation to be vastly different from those reported in other literature (for example, silvopasture). In these cases, we used the more conservative estimate. Key assumptions are described in Table 2, and more details are available in Supplementary Tables 33 and 34, and sections 3.1 to 3.4 of Supplementary Information.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

This analysis uses all publicly available datasets, primarily from USDA (for example, censuses, surveys, WASDE, AgStar) and EPA (for example, national GHG inventories). Data sources, assumptions and approaches used for the supply chain analysis and life cycle analysis are described and detailed in Supplementary Information. Data for Figs. 2 and 5 are provided in Supplementary Data 1 and are also available via figshare at https://doi.org/10.6084/m9.figshare.26488249 (ref. 41).

Code availability

Data analysis was conducted in both Python v3.11.2 and Microsoft Excel v16.65. For specific inquiries regarding the analyses please contact the corresponding author.

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Author contributions

R.E.O.P., K.J. and J.S. conceptualized the study. R.E.O.P., C.E.K., S.K., K.A.R., K.J. and J.S designed the study. R.E.O.P., D.R., N.S. and J.S. performed supply chain modelling and analysis. R.E.O.P., C.E.K., S.K., K.A.R., S.G., M.W. and E.Y. conducted mitigation opportunities analysis. R.E.O.P., C.E.K., S.K. and K.A.R. wrote the draft. All authors contributed to the review and editing.

Competing interests

The authors declare the following competing interests: this work was initiated with funding from McDonald's and supported further by the Walton Family Foundation. Authors affiliated with The Nature Conservancy (C.E.K., S.K., K.A.R., S.G., E.Y., M.W. and K.J.) and the Institute on the Environment (R.E.O.P., N.S., D.R. and J.S.) work with various companies in the beef industry. R.E.O.P. is the principal and founder of LEIF LLC, an LCA consulting firm working with companies across food and agriculture. These relationships could be perceived as potential competing interests.

Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s43016-024-01031-9.

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Data collection	No software or custom code was used in the collection of data
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Study description	Life cycle greenhouse gas emissions analysis of US beef production
Research sample	All counties producing feedstuffs, has pastureland, or confined animal feeding operations supporting beef production in the contiguous US, and all facilities processing beef.
Sampling strategy	N/A
Data collection	Use of USDA survey and census information, secondary literature sources, and US EPA data tables
Timing and spatial scale	Data ranges between 2007 and 2018. Supply chain data based on 2017. Emissions data based on average data across the available years in the timespan. Range of spatial scales- focus is on county and facility scale, with use of state, regional, and national scale data where necessary.
Data exclusions	Data from Hawaii and Alaska were excluded from the analysis due to the inconsistent data availability and relatively low contributions to total US beef production.
Reproducibility	All approaches, data sources, and assumptions are provided in detail in the supplemental information.
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☒	☐ ChIP-seq
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